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DISCUSSION PAPERS

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Telecommunications Infrastructure, Human Capital, and Economic Growth

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1 The first of three technical papers under the research entitled "Telecommunications, Information Technology, and Economic Growth." The author would like to thank Orest

Abstract

In the absence of other information, initial levels of human capital and infrastructure capital, together with the initial level of per capita income, are strong predictors of a country's future economic growth. However, these effects are not robust; when cross-country growth regressions are augmented with other variables, the effects of human and infrastructure capital often appear to be statistically insignificant. This insignificance may be due to an identification problem in cross-country growth regressions; it is unclear if they are estimates of a structural equation which gives the proximate determinants of economic growth, or a reduced form equation, in which all endogenous variables, such as human and infrastructure capital, can be replaced with their determinants. In order to identify the model, and allow the estimation of the proximate determinants of economic growth, we have to impose restrictions on the model using economic theory. Assuming a neoclassical growth model in which private capital is augmented with human and infrastructure capital we find that both human capital, in the form of total years of schooling of the workforce, and infrastructure capital, in the form of telephones per worker, have a significant impact on growth rates.

1. Introduction

Infrastructure capital and human capital play an important role in the growth process. However, both infrastructure capital and education provision have particular problems if left entirely to the market. Historically, infrastructure has had the attributes of a natural monopoly with economies of scale in production. Railway lines, road networks, telephone networks, and electricity distribution systems require links that represent large fixed costs, with relatively low marginal costs of actual use. Such distribution systems are natural monopolies since they typically have many links that have some excess capacity and so represent non-rival public goods. It is much more efficient to relieve congestion in a network by adding capacity on the congested links rather than having a competing firm replicate the whole system. These monopoly problems, together with the problems the private sector can face in raising the large initial capital outlays involved, have led to infrastructure being publicly provided in many countries.

While these arguments for public provision are good ones, they have become weaker over time. There has been increased recognition that public provision of infrastructure services can be very inefficient. Without the profit motive, and in the absence of competition, public provisions can be a very high-cost method of producing and maintaining infrastructure. In addition, in the absence of market prices, supply may very well fail to respond to demand (as appears to be the case with telephone provision in many developing countries, with the waiting period for a new telephone running into years).

New developments in technology have also been undermining the traditional arguments for public sector provision of infrastructure. Mobile telephones can operate independently of the older land line system. Cable television cables can be used as telephone lines. High bandwidth links are required for Internet data transmission, links that can also be used as telephone lines. The supply of telephone services in developed countries is becoming very competitive (see Harris and Kraft (1997) and Waverman and Sirel (1997)), while in developing countries there have been a number of successful initiatives to deregulate the industry (Spiller and Cardilli (1997)). A competitive private sector telecommunications industry, with regulation of any monopoly elements that remain, seems to be preferred model to follow.

In the case of roads, innovations in road pricing, such as allowing electronic charging, promise to allow the construction of an increased number of toll roads without the costs (both direct, for collection of the toll, and indirect, in the form of congestion at toll booths) that were prevalent in the past. The collection of user charges for roads may allow a much more rapid expansion of the road system in developing countries. However, the actual outcomes of toll road experiments in developing countries have been rather disappointing so far.

In the case of electricity supply there has been an increased recognition that while the distribution system is a natural monopoly, the efficient size of a power plant is often rather small relative to the size of the market, giving scope for competition and private sector involvement in electricity generation.

A real problem with the movement to private sector provision of infrastructure is the need for continuing government regulation of prices and access to competitors for the monopoly elements that remain. Such regulation has proved to be very complex, since the monopolist usually has many non-price methods through which he can exert market power, and, in addition, may have an information advantage over the regulator. In the presence of real competition these problems are not very worrisome since market discipline can be expected to prevent excesses. However, when there is a lack of real competition there may be a need for a highly sophisticated regulatory institution to oversee the operation of the market and perhaps construct "internal" markets. The World Bank's *World Development Report* (1994) looks at these issues in detail.

Turning to the case of education we have a rather different set of problems, given that there is no natural monopoly in the provision of schooling. In the case of investments in education, however, there may be severe problems of capital constraints for children from poor families. Even if the rate of return to education is high, poor families may lack the collateral required to borrow in order to finance this form of investment (whose costs involve not only the direct payments of school fees, but also the earnings forgone while attending school). In addition to this market failure argument there is also an argument that the state should intervene in the interests of children. Within a family children may be in a very weak position, with parents preferring the current income to the family from a child's work, which they control for themselves, rather than the future income a child might earn for their own benefit, if they were better educated. In addition, even if parents have the interests of their children at heart, they may be poor judges of the value of education to the children, particularly if they lack educational experience themselves. The failure of the capital markets, or this argument for paternalism, can justify intervention by the public sector. However, this does not imply that the public intervention must be in the form of public provision. Some countries are experimenting with a system of vouchers, with students having the right to attend school, but with schools competing for pupils. However, these experiments are as yet in the early stages.

In addition to these supply-side arguments for public provision there is also the possibility that infrastructure and education create large externalities in the form of positive spillovers, so that their contribution to total output exceeds the private returns to their purchasers. Rates of return estimates for infrastructure, using cost-benefit methods on individual projects (see World Bank (1994)), and education, using the wage premium that accrues to educated workers (see Psacharopoulos (1994)), give moderate estimates, typically in the range of 5% to 20% annual rates of return. However, these private rates of return may underestimate the social rates of return if there are important externalities to infrastructure and education.

Communications infrastructure may increase the extent of the market, allowing the exploitation of economies of specialization and scale, and generating increased competition. Education may have externalities in raising the capacity of the economy to absorb new ideas. In both cases, the rewards for these effects may accrue to the whole economy rather than the individual using the infrastructure or education. This implies that even without supply problems there may be a case for subsidies, or public provision in excess of the competitive market level, in order to gain from these externalities.

A central problem however with the externality argument is the difficulty in measuring these externalities. By their very nature they accrue to society as a whole rather than to the individual using the infrastructure or education directly. While some micro-economic evidence of spillovers does exist, in the main we look for their effects using data on aggregate income. The problem with this approach has been that different researchers have come up with wildly different estimates of the macroeconomic effects of infrastructure and education on economic growth. Gramlich (1994) reviews the empirical evidence on the aggregate output effects of infrastructure investment. While many cross-country studies find that education has a significant impact on economic growth (Barro (1991), Barro and Sala-i-Martin (1995), Birdsall and O'Connel (1999)), the result is not very robust and in some specifications education appears to have little or no effect on growth once we account for other variables. In particular, the inclusion of geographical variables seems to reduce the role of education (e.g., Gallup and Sachs (1998) find education to be insignificant while Sachs and Warner (1997) drop education measures completely from their growth regression).

While there is mixed evidence for the growth effects of education and infrastructure, the problem may lie more in the estimation techniques employed rather than in the nature of the underlying relationship. The problem with cross-country growth regressions is that they do not distinguish very well between factors that cause economic growth directly, such as capital accumulation and technological progress and those that cause economic growth indirectly, through their effects on capital accumulation and technological progress.

Infrastructure investment and education rates are the result of decisions that are subject to economic and political forces. For example, the demand for education rates may depend on life expectancy, since the payoff to education increases with the length of time it can be used, and access to international technology (perhaps via openness to the global economy) if the main purpose of education is to allow the adoption of new techniques. The public provision of education may depend on the political system. Once we capture these effects through life expectancy, openness, geography and political variables, education may have little residual power to explain growth since our model already explains education. This does not mean that education is unimportant, only that our model is unable to say whether it is education rates themselves, or the determinants of education rates, that cause economic growth.

A major part of this paper investigates this issue of what cross-country growth regressions say about the causes of growth. This leads to an argument that the variables that appear in a growth model should be constrained to accord with economic theory. Doing this, we find large impacts of education and telephone systems on economic growth. It may be that the quality of infrastructure provision is important as well its quantity (Hulten (1996)).

2. The Effects of Infrastructure and Human Capital on Economic Growth

While economic theory addresses the issue of the aggregate effect of public capital on economic growth, in particular emphasizing the possibility of spillovers to human capital (e.g., Lucas (1988)), and the tradeoff between the benefits of public capital and the distortions caused by the taxes needed to finance it (Barro (1990), Turnovsky and Fisher (1995)), the major questions are empirical. Just how important are human and infrastructure capital to growth and which types of education and infrastructure are most important? Unfortunately, despite a large amount of empirical research on these topics, the answers are not at all clear.

Evidence on the rates of return from education and infrastructure capital produces figures that are comparable with rates of return on private capital. Bils and Klenow (1996) review the evidence on rates of return to education using studies that cover 48 countries and conclude that each additional year of schooling raises wages by about 10%. Klenow and Rodriguez-Clare (1997) show that this level of microeconomic returns corresponds to a very low elasticity of output with respect to human capital in an aggregate production function, and a correspondingly small role for human capital in explaining aggregate output. The World Bank's *World Development Report* (1994) gives rates on return on infrastructure investments of between 5% and 25% per year. This suggests that infrastructure capital has roughly the same rate of return as private capital. However, these estimates neglect the possibility of externalities that may show up in aggregate macroeconomic performance but are not observable in microeconomic data.

We begin with a set of simple cross-section growth regressions in which initial income, education and infrastructure are the only determinants of future economic growth and find both types of capital have large and statistically significant impacts. However, when we augment the regressions with additional explanatory variables, including geographical variables, we find both education and infrastructure capital tend to have small and statistically insignificant coefficients.

This lack of robustness is somewhat alarming. It appears that the results we find are sensitive to the specification of the growth regressions being run. At one level the lack of robustness is not surprising. Levine and Renelt (1992) conduct extensive specification searches and come to the conclusion that no variable is robust in every specification. However, there is a deeper problem in evaluating the importance of capital inputs such as education and infrastructure in growth regressions. These capital inputs are endogenous and tend to grow with economic growth.

This is often seen as a technical problem in estimation, requiring us to use initial values of the capital stock as an explanatory variable, or if we include its growth rate over the period, instrumenting this endogenous growth rate with predetermined variables. However, even if we do this, there remains a fundamental difficulty. The growth rate of output in an economy can be explained in two ways. One way is to use the proximate factors, such as inputs of capital and labor, to explain variations in output. This is the structural approach. Another is to argue that these inputs are themselves the results of economic forces, and to replace the capital stock and labor input variables with their ultimate determinants (e.g., government policy, geography and climate). This is the reduced form approach. The problem is that in an ad hoc growth regression both structural and reduced form models will be estimated together, and the resulting parameter estimates will be a mixture of the parameters from the two models. It is therefore difficult to interpret the results of such an approach. In particular, we use theoretical arguments and a Monte Carlo study to show that the estimates produced by a fully specified growth model may differ substantially depending on the length of the period over which the growth is measured, since different time periods lead to different mixtures of the structural and reduced form coefficients.

However, if our growth regression includes initial values of all the relevant variables (both the proximate capital inputs and the fundamental reduced form factors), then as the length of period over which growth is measured increases the estimated coefficients will converge to the reduced form parameters, putting zero weight on the capital inputs. The rationale for this result is that in the long run the capital inputs, and the output they generate, are determined entirely by the reduced form and the initial capital stock variables have no impact. This may explain the lack of importance of initial capital stocks in long-run growth regressions with sufficient exogenous variables to determine the reduced form outcome.

If we are interested in the structural equation that determines how inputs of capital and labor determine output, a long-run growth regression is unlikely to generate meaningful results. Estimating a sequence of short-run growth regressions is more promising, but again we find little impact from our capital stock variables. While a growth regression tends to estimate the reduced form parameters as the time period becomes long, it does not, in general, estimate the structural parameters of the model as the time period under consideration becomes short. To do this, we must exclude from the regression variables that do not appear in the structural equation.

It follows that if we wish to estimate a structural equation, explaining growth by inputs of capital and labor, we are required to identify the model to be estimated from theoretical considerations. To do this we follow Mankiw, Romer and Weil (1992) and specify that output is due, in the first instance, to a production function. The neoclassical production function, in which output is due to technology, physical capital and labor, is augmented by education and infrastructure capital. This paper assumes that technology is worldwide and is captured by time dummies.

A serious problem in estimating such a relationship is the possibility of reverse causality from output to the capital inputs. Under some assumptions about the nature of the disturbances in the model, the production function can be estimated consistently as an error correction mechanism. This has a natural interpretation as a cross-country growth regression in which the growth rate of output responds to the initial level of income per capita and capital stocks per capita. That is, we estimate a growth regression where the explanatory variables are restricted to those that our theory puts in the structural equation being estimated. In addition, on theoretical grounds, we expect short run growth regressions to give the best results.

Doing this we find that both human capital and infrastructure capital appear to be important factors in the production function. In addition we find some support for the idea that there are constant returns to capital taken as a whole, supporting the endogenous growth model.

3. Empirical Cross-Country Growth Regressions

We begin with some simple descriptive regressions aimed at explaining the rate of growth of GDP per worker over the period 1965-1990. The data for GDP per worker is on a purchasing power parity basis and comes from the Penn World Tables (5.6), (see Summers and Heston (1991) for a description of this data). The growth rate of GDP per worker is expressed as annual average percentage income growth over the period. In table 1 we use as our explanatory variables the log of initial income per capita, the log of the average years of education of the workforce and the log of initial telephones per capita. The education data is from Barro and Lee (1993) while the telephone data is from Canning (1998).

In growth regressions such as these, a negative coefficient on initial income is often taken as evidence of convergence. If no other variables (apart from a constant term) were included, a negative coefficient on initial income would indicate unconditional convergence; rich countries grow more slowly than poor countries, so countries tend to become more similar in terms of their income levels as time passes. The results in column one indicate that there is no tendency for income levels to converge over time; in fact there is some evidence for divergence, since the positive coefficient on initial income suggests that countries that are richer at the beginning of the period grow faster.

However, once we add our initial education or telephone stocks, individually or together, we find strong evidence of conditional convergence, with the initial capital stocks having a negative and statistically significant impact on subsequent economic growth. Rich countries grow more slowly than poor countries but, for a given level of initial income, we would expect a country with a higher level of education, or a greater number of telephones per capita, to grow more quickly. In this case countries will converge over time, but not to the same level of income. They each converge to their own steady state level of income where the negative effect of their income level exactly offsets the positive effects of the telephone and education stocks.

The problem with table 1 is of course that the results may reflect omitted variable bias. The capital stock variables may simply be proxies for some hidden variables and so represent a statistical correlation rather than a causal relationship. One way to address this problem is to add additional explanatory variables in order to reduce the likelihood of omitted variable bias.

In table 2 we add a number of variables to the regression. Log life expectancy is used by Barro and Sala-I-Martin (1995), who find it to be important and robust. Openness is a composite measure of the role of market forces and lack of trade barriers in an economy taken from Sachs and Warner (1997), who argue that it is an important determinant of economic performance. The geography variables (percentage of land in the tropics and a dummy variable for being landlocked) are taken from Gallup and Sachs (1998), while the demographic variables (log of the ratio of working age to total population and the differential growth rate of the working age population to the total population) are used by Bloom and Williamson (1998) and Bloom, Canning and Malaney (1999). These variables are not intended to be a comprehensive list but are merely a selection of those that have been put forward as important parts of the growth process.

Table 1
Simple Growth Regression on 25 Year Period

Dependent Variable: Annual Average Percent Income per Capita Growth 1960-1985

Constant	0.291	6.683	13.72	12.24
	(0.24)	(3.12)	(4.25)	(3.52)
log initial income per capita	0.267	-0.875	-2.031	-1.801
	(1.72)	(2.81)	(4.01)	(3.37)
log initial average years of education		1.714		1.222
		(4.78)		(2.76)
log initial Telephones per capita			1.255	0.710
			(4.78)	(2.21)
Number of Observations	105	83	100	81
R squared	0.02	0.26	0.25	0.30
R squared adjusted	0.01	0.24	0.23	0.27

Table 2
Growth Regressions on 25 year period

Dependent Variable:	Annual Average Percent Income per Capita Growth 1960-1985			
Constant	5.107	9.007	9.658	11.72
	(1.04)	(1.98)	(1.80)	(2.58)
Log initial income per capita	-1.803	-1.967	-2.209	-2.247
	(6.53)	(8.40)	(6.11)	(6.63)
% of land area in the tropics	-0.665	-1.131	-0.557	-1.037
	(1.73)	(3.09)	(1.43)	(2.78)
Openness	1.824	1.691	1.731	1.657
	(5.32)	(5.81)	(5.38)	(5.84)
Landlocked	-0.761	-0.693	-0.834	-0.794
	(2.54)	(2.88)	(2.56)	(3.23)
Log life expectancy	3.291	2.626	2.677	2.278
	(2.56)	(2.39)	(1.99)	(2.17)
Log working age ratio	6.045	6.227	5.806	5.837
	(2.26)	(2.61)	(3.58)	(2.47)
Growth of working age -growth of total pop	2.405	2.988	2.363	2.968
	(3.58)	(5.13)	(3.58)	(5.26)
Log initial average years of education		0.191		0.106
		(0.75)		(0.39)
Log initial telephones per capita			0.321	0.261
			(1.58)	(1.18)
Number of Observations	90	73	89	73
R squared	0.72	0.80	0.73	0.81
R squared adjusted	0.70	0.78	0.70	0.78

Using just these variables in column 1 of table 2 gives a fairly high R^2 with each of the variables being statistically significant (though for tropics only at the 10% significance level). Adding our capital stock variables to this base regression gives much smaller coefficients than in table 1, and none that is statistically significant. Similar results hold if we disaggregate the education stock variable (using stocks of primary, secondary and tertiary level education) and use additional types of infrastructure capital (electricity generating capacity and paved roads). Of course, it is possible to achieve statistically significant coefficients on our capital stock variables in some specifications (e.g., Sanchez-Robles B. (1998)). However, it is unclear that this achieves very much since the results will not be robust, unless one specification is preferred to another on a priori grounds.

One interpretation of these results is that, once we control for other variables, the effects of education and infrastructure capital on long-run economic growth are small. This may indeed be the correct interpretation, but it does not imply that education and infrastructure are unimportant in the growth process.

4. The Growth Process and Cross-country Growth Regressions

In order to understand the results in the previous section let us put them in the framework of a theory of economic growth. Since the purpose of this section is merely illustrative we will concentrate on a simple model. Let y(t) denote a vector of endogenous variables in a country at time t. Let x be a vector of exogenous variables and assume

$$\Delta y(t) = Ay(t-1) + Bx + \varepsilon(t)$$

where $\varepsilon(t)$ is an error term. For simplicity let us assume that $\varepsilon(t)$ is independently and identically distributed. Note that we could index each variable with a subscript j to denote the country, however, this is taken as implicit. While the exogenous variables x are assumed not to vary over time, they are allowed to vary across countries. We assume that the laws of motion of the economy, expressed in the coefficient matrices A and B, are the same in every country. If we assume that the endogenous variables are expressed in logs, the difference terms are growth rates, and the model says that the growth rates of the endogenous variables depend on one period lags of the endogenous variables and the exogenous variables.

Now, letting $C = A + I$, and $R = A^{-1}B$, we can derive the reduced form of the system

$$y(t) = A^{-1}Bx + u(t) = Rx + u(t)$$

where

$$u(t) = \sum_{s=0}^{\infty} C^s \varepsilon(t-s)$$

We can now define the long-run equilibrium of the system as

$$y^* = \lim_{T \to \infty} E(y(T)) = A^{-1} Bx = Rx$$

The system will converge to the steady state Rx with a stationary error term (provided the matrix C satisfies a stability condition (its eigenvalues have modulus less than one) which we assume to hold). In particular, if income per capita is y_1

$$y_1^* = r_1 x$$

where r_1 is the first row of the matrix R. It follows that the long-run growth of income per capita is given by

$$\lim_{T \to \infty} \Delta^T y_1 = \lim_{T \to \infty} y_1(T) - y_1(0) = \lim_{T \to \infty} E(y_1(T)) + u(T) - y_1(0) = r_1 x - y_1(0) + u(T)$$

As T grows large, u(T) is asymptotically uncorrelated with $y_1(0)$ (assuming the stability condition). This means that the error terms are uncorrolated with the explanatory variables, and the equation can be estimated by ordinary least squares. Over the long run, the growth rate of income per capita is determined entirely by the exogenous variables in the reduced form. Including the initial values of the other endogenous variables to a long-run growth regression adds spurious variables, and the expected value of the coefficient on each of these variables is zero. These endogenous variables will be correlated with the exogenous variables that drive long-run economic growth but they add no information to a long-run growth regression since they are asymptotically uncorrelated with the error term, u(T). The only information these initial endogenous variables contain is the fact that they are correlated with the exogenous variables. In a misspecified equation, where important exogenous variables are excluded the initial values of the endogenous variables may act as proxy variables. However, in a properly specified equation they add nothing. Note that while the endogenous variables are correlated with the exogenous variables they contain "measurement error" (the disturbance term at time zero) and so if both (that is, the exogenous and endogenous variables together) are included, the exogenous variables will dominate in the regression.[1]

In table 3, we report some Monte Carlo simulations based on the following simple model

$$\Delta y_1(t) = 0.4\, y_2(t-1) - 0.2\, y_1(t-1) + \varepsilon_1(t), \quad \Delta y_2(t) = 0.1\, x - 0.1\, y_2(t-1) + \varepsilon_2(t)$$

where the error terms are independent and identically distributed N(0, 1) and the initial values of each variable are independent random draws from N(0, 1). The reduced form of this model is given by

$$y_1(t) = 2x + u_1(t), \quad y_2(t) = x + u_2(t)$$

where the error vector u(t) is stationary but has a complex autoregressive structure as set out above.

The process is allowed to run for 50 periods to settle down and then we estimate a "cross-country" growth regression over a subsequent number of periods. The model is stationary and allowing it to run for 50 periods before estimation allows it to find a representative set of "initial conditions" from which to estimate our growth equation. We have 1000 "countries" in our sample, each with the same system of equations but with different initial values of the variables, though note that x, while differing across countries, is fixed over time.

The results are quite different depending on the period of estimation. With one period growth rates we essentially estimate the structural equation where y_1 converges toward y_2 and x is irrelevant. However, in the 50 period regression we estimate the reduced form; the initial value of y_2 becomes irrelevant and only x matters. For regressions over 10 and 25 periods we essentially estimate, as the steady state of the system, a linear combination of the structural equation and the reduced form, with weights depending on the length of the estimation period.

In practice, cross-country growth regressions are run over periods ranging from 20 to 30 years and the coefficients we observe will be a mixture of the reduced form and structural equations. It follows that the "steady state" implicit in the growth regressions will vary with the length of the period under consideration and will be difficult to interpret, though if the period under consideration is long enough, a reduced form interpretation may be applicable.

In table 4 we report growth regressions using the same variables as in table 2, but with growth rates measured over five-year periods. The explanatory variables are now measured at the beginning of the period, or over the five-year period. In addition, time dummies are added to allow for worldwide level effects in steady state income per capita. There is in fact surprisingly little change in the parameters estimated. The coefficients on our capital stock variables are still small and statistically insignificant. There appears to be some increase in the effect of life expectancy, and a reduction of the impact of the differential growth of working age to non-working age population, in this short run analysis. This is consistent with life expectancy being an endogenous variable the effect of which falls the period of estimation increases while population growth may have important multiplier effects that only appear in the longer run.[2]

Table 3
Monte Carlo Simulations

Dependent Variable	1 period change y1	10 period change y1	25 period change y1	50 period change y1
Constant	0.032	0.127	-0.199	-0.098
	(1.04)	(1.24)	(1.44)	(0.77)
Initial y1	-0.200	-0.943	-1.097	-0.995
	(18.4)	(26.0)	(22.6)	(22.1)
Initial y2	0.406	1.019	0.464	0.062
	(20.7)	(15.5)	(5.31)	(0.76)
Initial x	0.028	0.911	1.645	1.855
	(0.79)	(7.71)	(10.4)	(12.6)
N	1000	1000	1000	1000
R squared	0.31	0.41	0.44	0.50
R squared adjusted	0.31	0.41	0.44	0.50
Implied steady state coefficients				
Y2	2.03	1.08	0.43	0.06
X	0.14	0.97	1.50	1.86

Table 4

Growth Regressions on 5 year periods

Dependent Variable: Annual Average Percent Income per Capita Growth in five-year periods 1960-90

Constant	time dummies	time dummies	time dummies	time dummies
Log initial income	-1.756	-1.917	-1.870	-2.208
Per capita	(6.58)	(6.73)	(4.39)	(4.80)
% of land area	-0.870	-1.062	-0.810	-1.129
In the tropics	(2.37)	(2.67)	(2.14)	(2.74)
Openness	2.321	2.276	2.254	2.243
	(7.11)	(6.99)	(6.68)	(6.71)
Landlocked	-0.724	-0.368	-0.682	-0.460
	(2.16)	(1.14)	(2.12)	(1.41)
Log life expectancy	5.207	5.813	4.389	5.339
	(4.09)	(4.04)	(3.27)	(3.75)
Log working age ratio	4.108	4.506	3.289	2.798
	(1.88)	(1.92)	(1.47)	(1.20)
Growth of working age	0.987	1.239	1.042	1.338
-growth of total pop	(3.31)	(4.07)	(3.38)	(4.37)
Log initial average		-0.163		-0.156
years of education		(0.63)		(0.55)
Log initial telephones			0.167	0.263
per capita			(0.77)	(1.15)
Number of Observations	607	512	575	494
R squared	0.32	0.37	0.34	0.38
R squared adjusted	0.31	0.35	0.32	0.36

When we estimate a short run growth regression, based on our theoretical structure, we clearly have that u(1) and y(0) are correlated and adding the initial values of the endogenous variables adds information. In fact, when estimating a one-year growth equation we are estimating the structural equation for the system. One way of finding the parameters of the structural equation in this model is simply to estimate the structural equation directly. In this simple model this estimation poses no problems and can be achieved by ordinary least squares. In a more general framework, in which there may be reverse causation from y_1 to y_2, we can instrument y_2 with the exogenous variable x in a cross-country regression. The problem with estimating the structural equation directly is that we need to decide which variables are in the structural equation and which are not. Such identification is usually not possible on statistical grounds alone; we require the imposition of a priori knowledge to identify the structure of the model.

The aim of this section has not been to provide a comprehensive theory, but simply to show that the results of cross-country growth regressions need to be interpreted with care. A more general model would take into account the fact that the exogenous variables vary over time as well as across countries, but similar identification issues would remain.

In order to fully understand the growth process we would ideally like to estimate the full structural model. This would not only tell us the proximate determinants of economic growth, but show us how these determinants are themselves determined. We might imagine explaining output by using factor inputs and total factor productivity, and then explaining the accumulation of factor inputs and growth of total factor productivity by their own structural equations as in Ghali (1998). For example, we might show how political instability affects total factor productivity and the accumulation of capital, and in addition, in a further structural equation, what factors determine political instability. Such an undertaking is clearly going to be an enormous endeavor.

The use of cross-country growth regressions is a shortcut where we try to bypass the problem of estimating the entire structural model. It should come as no surprise that a one-equation model cannot identify the parameters of the multi-equation structural system. This does not imply that such cross-country regressions provide no information; if estimated over a sufficiently long time period they may identify the reduced form of the model, the fundamental exogenous factors that determine long-run growth. Even if estimated over a short or intermediate time period, generating mixtures of the reduced form and structural parameters, they may still provide insights if interpreted with care.

5. Estimating an Augmented Neoclassical Growth Model

In order to understand the growth process we require a structural model based on theoretical considerations. Suppose we assume that the proximate determinants of output are inputs of labor, physical capital, human capital, infrastructure capital and total factor productivity. Further imposing a Cobb Douglas production function with constant returns to scale, we can derive

$$y(t) = c(t) + \alpha\, k(t) + \beta\, h(t) + \gamma\, i(t) + u(t)$$

where y is log output per worker, c is log total factor productivity, k is log capital per worker, h is log human capital per worker and i is log infrastructure capital per worker. Two fundamental problems occur in estimating such a model. The first is that total factor productivity, c(t), is not observed and must be proxied in some way. The second is that the capital stock variables may be endogenous, with higher income leading to higher investment in all forms of capital, precluding simple ordinary least squares estimation in levels. Mankiw, Romer and Weil (1992) attempt to overcome these problems by assuming a worldwide common level of technology, and replacing the stocks of physical and human capital with saving rates and school enrollment rates respectively, which are assumed exogenous. Garcia-Mila, McGuire and Porter (1996) estimate a production function including infrastructure variables in first differences.

We follow Mankiw, Romer and Weil in assuming a common worldwide level of technology, and so proxy c(t) by a set of time dummies reflecting exogenous shocks to total factor productivity. Instead of looking for instruments for the capital stock variables we can derive a growth equation by assuming that the error term, u(t), has an autoregressive structure

$$u(t) = \varepsilon(t) + p\, u(t-1)$$

where $0 < p < 1$ is the autoregressive coefficient denoting the persistence of shocks in the system.

Rearranging terms gives us

$$\Delta y_t = (1-p)(c_{t-1} + \alpha\, k_{t-1} + \beta\, h_{t-1} + \gamma\, i_{t-1} - y_{t-1}) + \Delta c_t + \alpha\Delta k_t + \beta\Delta h_t + \gamma\Delta i_t + \varepsilon_t$$

Growth in income per worker can be decomposed into an error correction mechanism plus the impact of growth of total factor productivity and inputs. Now let us assume that

$$\varepsilon_t = -(\Delta c_t + \alpha \Delta k_t + \beta \Delta h_t + \gamma \Delta i_t) + \sum_{s=1}^{k} (\phi_{cs} \Delta y_{t-s} + \phi_{ks} \Delta k_{t-s} + \phi_{hs} \Delta h_{t-s} + \phi_{is} \Delta i_{t-s}) + v_t$$

where v is an independent, identically distributed, white noise term. This specification implies that current investment in factor inputs does not immediately enter into the production process. The assumption that current input growth has no effect on output seems plausible in an model using annual data. Current growth of inputs has no impact, and growth of inputs in the recent past may have a delayed effect until they come fully on stream.[3] This gives rise to the lagged terms in the growth rate of the inputs; the lags subtract out from current output the effect on any inputs that have not yet come on stream. The lag structure has a maximum length k, meaning that after k years all new inputs are being fully utilized. The advantage of this assumption is that it relieves us of the need to instrument the contemporaneous input growth effects. We assume that the error term v sub t is independent and normally distributed. This gives us the equation to be estimated[4]

$$\Delta y_t = (1-p)(c_{t-1} + \alpha k_{t-1} + \beta h_{t-1} + \gamma i_{t-1} - y_{t-1})$$

$$+ \sum_{s=1}^{k} (\phi_{cs} \Delta y_{t-s} + \phi_{ks} \Delta k_{t-s} + \phi_{hs} \Delta h_{t-s} + \phi_{is} \Delta i_{t-s}) + v_t$$

We estimate this equation using ordinary least squares, since by assumption the error term is now uncorrelated with any of the explanatory variables, and report the results in table 5. Note that we multiply though the (1-p) term so the coefficient on log income per worker is (1-p) while the coefficients on the capital stocks are their coefficients in the production function multiplied by (1-p).

The emphasis in this regression is on output and capital stocks per worker rather than the per capita approach we used previously. This is because the production function theory predicts output per worker and not output per capita. We would need to include data on workers per capita to link the two (see Bloom, Canning and Malaney (1999)). Data on income per worker again comes from Summers and Heston (1991) while capital stock data are constructed from the Summers and Heston investment series using an initial capital output ratio of 3 in 1950 and a 7% depreciation rate.[5] The human capital and telephone data are from the same sources as before though the telephone data is now deflated with the number of workers (taken from Heston and Summers) rather than the total population. Prichett (1996) argues that investment data on infrastructure may not be indicative of capital stock accumulation because of wide variations in the price of infrastructure across countries, so it may be better to use Canning's (1998) direct estimates of the infrastructure stock.

When the period over which growth is estimated is 5 or 25 years we do not use lags of the growth rates; that is we assume that after 5 years all capital is operating at its full potential.

However, in these cases the assumption that investment within the period is irrelevant is unlikely to be true. The best regressions for estimating the structural equation are those using annual data. Here we use the last two years' growth rates of the income and capital variables to correct for short-term impacts. The assumption that capital investment during the year does not impact output in that year seems reasonable. An additional advantage of the model using annual data is that in this framework we can avoid the econometric problems that occur in panels with a small number of observations in the time dimension (e.g., see Islam (1995), and Hoeffler (1999)).

The regressions using annual data, reported in the last two columns of table 5, indicate that when we include only physical capital and human capital each has a coefficient of about 0.5 in the Cobb Douglas production function. These are somewhat higher than the coefficients found by Mankiw, Romer and Weil and imply that the production function may exhibit constant returns to capital, which is compatible with endogenous growth. When we include log telephones per worker, the coefficients on physical and human capital drop to around 0.3 while that on telephones is 0.25. The coefficient on telephones is surprisingly high and may be due to measurement error in the physical capital stock or telephones acting as a proxy for a more general stock of infrastructure capital.

The results reported in table 5 are not intended to be definitive. They rely a great deal on the assumptions used to identify the structural equation and to allow estimation of its parameters. A greater dissaggregation of the capital stock could be employed. Proxies could be employed to allow for cross-country differences in total factor productivity. The reverse causality issue could be addressed using instruments rather than restrictions on the dynamics of the error structure. However, all these issues need to be addressed in the framework of economic theory since the correct proxies and instruments need to be determined primarily on theoretical grounds.

6. Conclusion

Cross-country growth regressions need to be interpreted with care. In general, their estimated coefficients are combinations of parameters from the reduced form and structural models of the underlying growth process. This combination, and the resultant coefficient estimates will vary with the time span used in the growth regression, though if a very long time span is used we tend to estimate the reduced form parameters.

This means that cross-country growth regressions over long time periods are unlikely to help us identify and estimate the structural equations of a model, in particular how capital stocks affect output. In the long run it is not the capital stocks that matter but their determinants, since in the long run capital stocks are endogenous. To estimate the structural equation representing the production function we require the use of theoretical considerations to determine which variables should be included and how we can overcome the problem of reverse causality.

One approach to this problem is followed here, using a simple production function framework and imposing restrictions on the dynamics of the error structure. This has the advantage that it leads to estimating a growth regression, though with a restricted set of explanatory variables, and with an emphasis on short run growth rather than the long run.

The lack of importance of initial levels of human capital and infrastructure variables in long-run cross-country growth regressions is entirely compatible with there being important inputs into the production function. They do appear to be important when we restrict the model to be consistent with a production function. Further progress in estimating their effects will require investigation into which identifying assumptions are most plausible on theoretical and empirical grounds. In particular we need to identify some variables that can proxy for total factor productivity and others that can act as instruments for our capital inputs. Both these issues pose serious challenges.

Table 5

Growth Regressions using Production Function Specification

Dependent Variable:	Annual Average Percent Income per Worker Growth					
	over 25 years	over 25 years	over 5 years	over 5 years	over 1 year	over 1 year
Constant	7.816 (3.60)	11.01 (2.91)	year dummies	year dummies	year dummies	year dummies
log initial income per worker	-1.550 (1.98)	-1.608 (1.97)	-1.538 (2.96)	-1.650 (2.92)	-2.014 (3.44)	-2.145 (4.85)
log initial capital per worker	0.619 (0.96)	0.185 (0.24)	0.898 (2.21)	0.282 (0.68)	1.135 (2.44)	0.641 (1.72)
log initial average years of education	1.404 (4.06)	1.164 (2.51)	0.926 (3.73)	0.602 (2.06)	0.986 (3.43)	0.669 (2.19)
log initial telephones per worker		0.405 (1.15)		0.628 (2.62)		0.537 (2.49)
Number of Observations	82	80	577	549	2724	2544
R squared	0.20	0.20	0.20	0.21	0.10	0.10
R squared adjusted	0.16	0.16	0.15	0.16	0.09	0.09
Implied elasticity of output with respect to:						
physical capital	0.40	0.12	0.58	0.17	0.56	0.30
human capital	0.91	0.72	0.60	0.36	0.49	0.31
telephones		0.25		0.38		0.25

regressions for one year and five year growth rates include time dummies
regressions for one year growth rates include 2 lags of the growth rate of each explanatory variable and the growth rate of income per worker (coefficients not reported)

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Endnotes

1.In addition, adding growth rates of the endogenous variables, and instrumenting them, does not help. Instrumenting with lagged values of the endogenous variables will add nothing asymptotically since these lagged values will become uncorrelated with the future growth rates. The only valid instruments for the endogenous variables are exogenous variables that are in the reduced form, but these are already in use. We could estimate a structural equation by using as instruments exogenous variables form the reduced form that do not appear in that structural equation and eliminate these exogenous variables from the direct estimation of that equation. But this is the exactly the identification issue that needs to be addressed, and that requires imposing a priori theoretical restrictions on the structural model.

2. This holds even if we instrument the growth rates of population (see Bloom, Canning and Malaney (1999)).

3. In addition these lagged growth terms may pick up business cycle and short run consumption multiplier effects.

4. This is similar to error correction mechanisms used to estimate cointegrating relationships. However, here the results hold independently of the variables being stationary or non-stationary since we obtain consistency from the cross section dimension rather than the time dimension.

5. The capital stock estimates are remarkably insensitive to changing the initial capital stock and the depreciation rate. The effect of the initial level of the capital stock decays quite quickly over time.